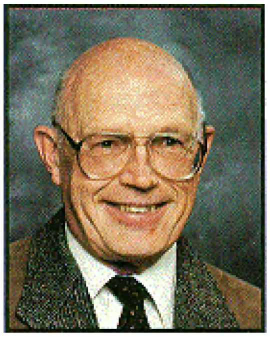
Precautions on Polar-plot balancing



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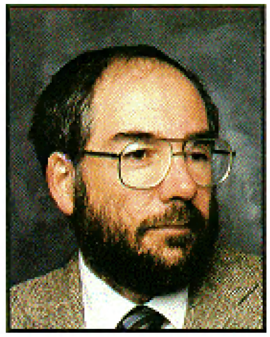

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For many years, Bently Nevada Corporation has presented and encouraged Polar-plot balancing because this method also yields valuable data of the performance characteristics of the machine being balanced along with the balance data. The calibration weight method at one speed using influence vectors yields very little information of the machine's overall performance characteristics.

However, it is very easy at low speeds below a resonance to have phase readings that you might not expect; that is, the High Spot and the Heavy Spot **are not always together at low speed.** Specifically, when probes are located near a bearing or a seal, the damping term may introduce a small to large lag angle.

Figure 1 shows a simple rotor containing an imbalance. Assume that the rotor rotates at a low speed below resonance. Notice that the Heavy Spot (imbalance) and the High Spot are nearly together as observed near the disk, but near the bearing the observed shaft motion High Spot lags the shaft bow considerably (Figures 3 through 6).

In simple mathematics, the synchronous dynamic stiffness observed near the mass at low speed for this rotor is approximately the shaft stiffness, K_s. However, the synchronous stiffness at the bearing is

$$K_B + j\Omega(1-\lambda)D$$

where

- K_B is the longitudinal wedge stiffness of the bearing
- Ω is the rotative speed
- λ is the fluid average circumferential velocity to rotative speed ratio
- D is fluid-film radial damping

The motion at the mass $\overline{z}_m$ is the force of imbalance, F_u, at angle ϕ_u divided by K_s, approximately,

$$\overline{z}_m \approx \frac{F_u < \phi_u}{K_s}.$$

Since the phase angle of a spring stiffness is zero, the motion $\overline{z}_m$ at the mass has the same phase as the phase angle of the imbalance (the Heavy Spot and High Spot are together).

The motion at the bearing, however, is approximately $\overline{F}_u$ divided by the synchronous stiffness at the bearing, $K_B + j\Omega(1-\lambda)D$, or

$$\overline{z}_B \approx \frac{\overline{F}_u[K_B - j\Omega(1-\lambda)D]}{K_B^2 + \Omega^2(1-\lambda)^2 D^2}$$

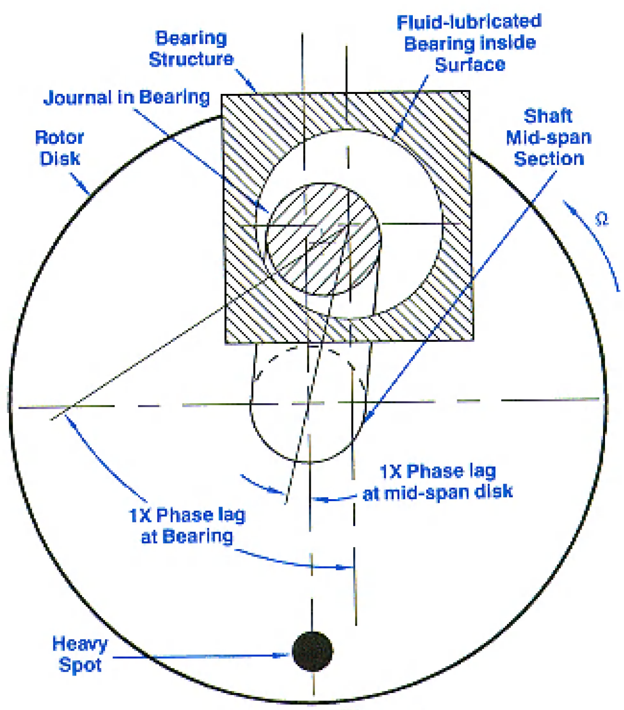

Figure 1

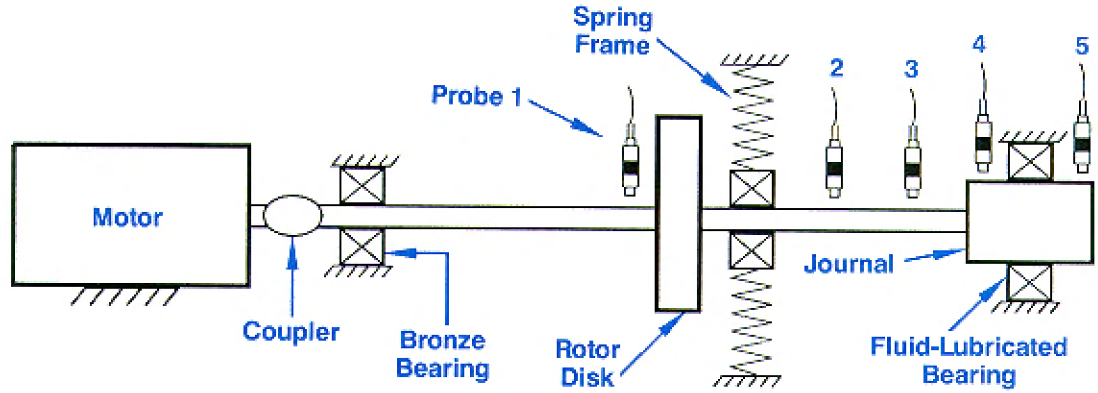

Figure 2

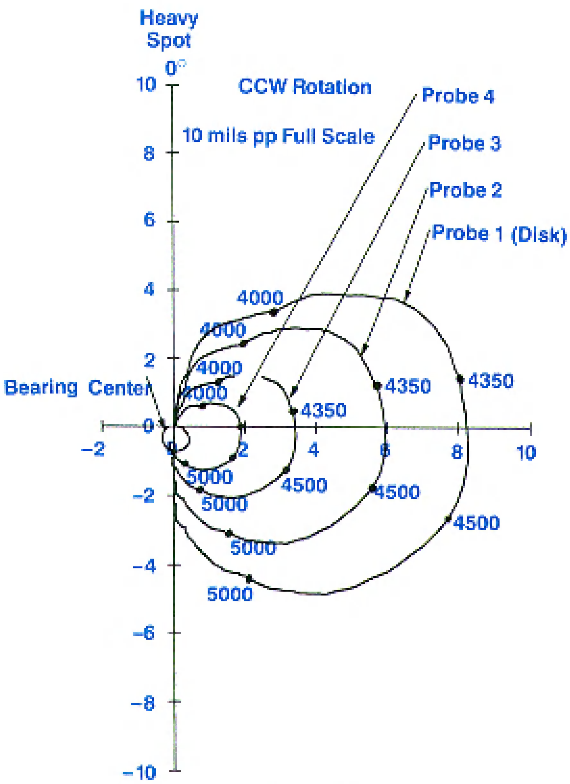

Figure 3

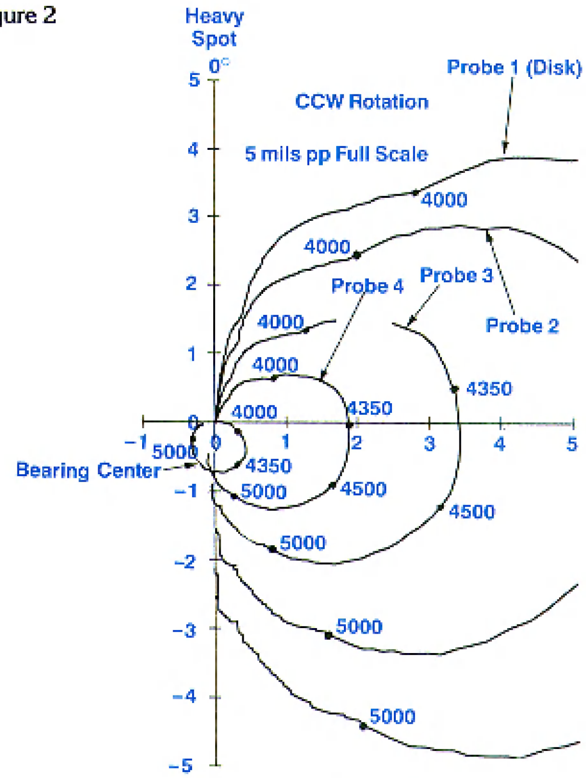

Figure 4

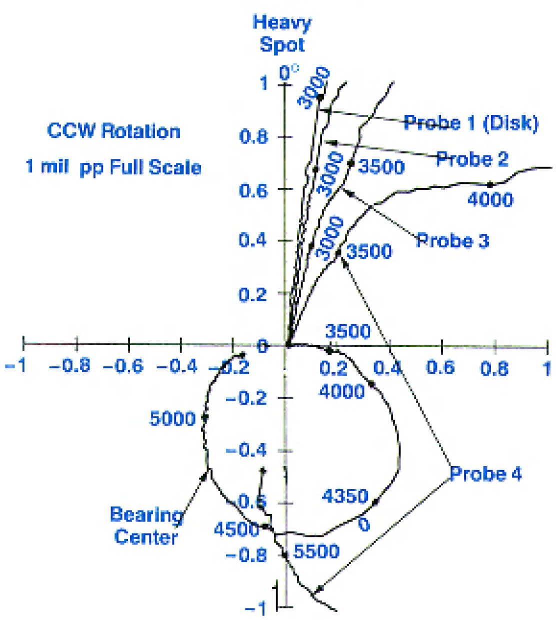

Figure 5

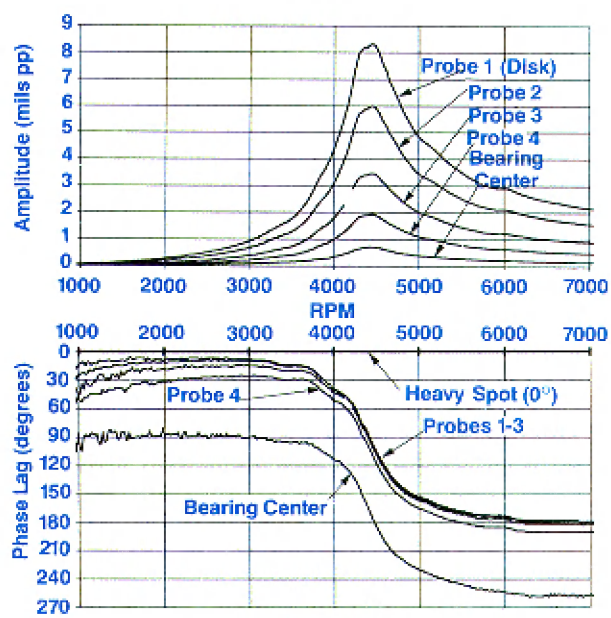

Figure 6

It is obvious that the $-j\Omega(1-\lambda)D$ term in the numerator of the $\overline{z}_B$ equation contributes to lagging the phase angle of the High Spot since λ is usually a ratio between 0 and 1. If K_B and $\Omega(1-\lambda)D$ are the same magnitude, the phase lag is, of course, 45°. If the synchronous damping term $\Omega(1-\lambda)D$ were ten times as large as K_B, the High Spot would lag the Heavy Spot by arctan 10 = 84.3°. This can happen and does happen at very low speeds far below the lateral resonance ("critical") speed range, as observed near the bearing or seal.

As a result, if you do Polar-plot balancing at speeds below resonance, assuming the Heavy Spot and High Spot are together, you may simply chase around the rotor with successive shots when the probes are in their usual locations.

Calibration weight balancing using influence vectors does not get tricked by this (although it may be tricked by nonlinearity, non-symmetry, and other parameters). In fact, the angle of the influence vector yields an indication of the strength of the damping term.

To illustrate rotor response in and near a fluid-lubricated bearing, an experiment was conducted using a rotor with a mid-span disk supported between two bearings (Figure 2). The weight of the mid-span disk was supported by springs in such a way as to center the journal in the bearing. One of the bearings was a relatively high-stiffness bronze bushing; the other bearing was an oil-lubricated journal bearing. The driving motor was installed via a flexible coupling on the opposite side of the bronze bushing from the rotor disk.

One vertical eddy-current probe (Probe 1) was installed to observe the rotor shaft immediately adjacent to the mid-span rotor disk. Two more vertical probes (Probes 2 and 3) were installed to observe the rotor shaft at two different locations, approximately equally spaced, between the mid-span rotor disk and the fluid-lubricated bearing. Finally, two additional vertical probes (Probes 4 and 5) were installed immediately adjacent to (and on opposite sides of) the fluid-lubricated bearing. Probes 4 and 5 directly observed the journal. The rotor was then balanced.

After balancing, a known imbalance mass was installed in the rotor disk at 0° phase angle relative to the vertical probes. The rotor was slowly ramped up in speed, and vibration data from all five probes was taken at speeds from 300 rpm to 7000 rpm. The data from Probes 4 and 5 was interpolated to yield the rotor (actually journal) response at the center of the bearing.

The results are presented in Figures 3 through 6. Figures 3 through 5 show slow-roll-compensated, 1X-filtered, Polar plots of the data from vertical Probes 1 through 4 and the interpolated, bearing-center, journal response (also 1X-filtered and compensated). The figures represent the view as seen from the counterclockwise-rotating driving motor, and operating speeds in rpm are indicated to aid in comparison. Figure 6 presents a Bode plot of the same data.

Figure 3 is a Polar plot of the vibration data plotted at 10 mils peak-to-peak full scale. Figures 4 and 5 show the same data as Figure 3 but plotted at 5 mils peak-to-peak full scale and 1 mil peak-to-peak full scale, respectively. The outermost plot is the rotor response from Probe 1 located near the mid-span disk. The other plots in this figure show the rotor response at the different probe locations, each one successively closer to the bearing. The interpolated journal response in the fluid-lubricated bearing is the smallest circle in the middle of the plot family. Remember that the imbalance mass in this disk (the Heavy Spot) is located at 0°. It is clear that the rotor response at the mid-span disk is much as expected with a low speed phase lag of close to 0° and a high-speed phase lag of close to 180°. The rotor first balance resonance occurs at about 4450 rpm with a response of 8.3 mils peak-to-peak at a phase lag of approximately 96°. (See Figure 6 for a Bode plot of the same data.)

Note that probes located successively closer to the fluid-lubricated bearing reveal a successively decreasing rotor amplitude. Because of this decreasing amplitude, data from probes closer to the bearing more clearly reveal the influence of the bearing fluid forces on the rotor response. Data from Probes 1-3 show relatively little fluid-force effect, especially at speeds above resonance. For probes located outside the bearing, the largest fluid-force effect can be seen in the data from Probe 4, which is located immediately adjacent to the bearing.

Figure 6 shows that the rotor response at Probe 4 lags the Heavy Spot by about 30° at speeds below resonance. Note also that the lag is most pronounced at a very low speed (1000 rpm) where the rotor at this location has a phase lag of nearly 50°. In the bearing center the rotor exhibits the largest phase lag relative to the Heavy Spot and a nearly 90° lag relative to the mid-span disk (Figure 5 clearly shows the very different rotor behavior at the center of the bearing). This large phase lag, relative to the mid-span disk, is nearly constant over the entire speed range of the rotor.

As we have seen, the amount of the phase lag depends on how close the probe is to the fluid-lubricated bearing. In general, the dynamic response of a rotor at locations well away from a fluid-lubricated bearing or seal (such as the locations of Probes 1 through 3 in this experiment) shows little influence by fluid forces in the bearing. The dynamic response of a rotor at a location **very close to** a fluid-lubricated bearing or seal (such as the location of Probe 4 in this experiment) may exhibit a phase lag that is significantly larger than expected at low speed. Finally, the dynamic response of a rotor at a location **in** a bearing or seal can exhibit a much larger than expected phase lag throughout the entire speed range (such as the bearing center curve in Figure 6).

This difference in phase can make Polar-plot balancing difficult unless the phase lag (which is primarily caused by damping but which may be contributed to by the fluid inertia effect) is taken into account. Data from probes located near a fluid-lubricated bearing or seal are usually OK, but data from probes located very close to or in a fluid-lubricated bearing or seal may exhibit a larger than expected phase lag relative to the Heavy Spot. *(Refer to related article on Attitude Angle on page 31.)* ■